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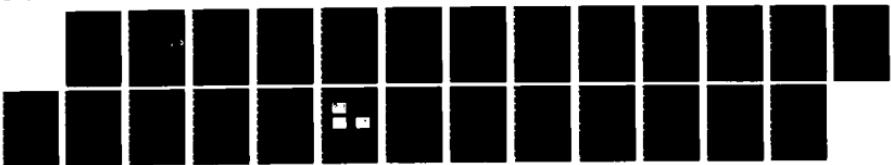
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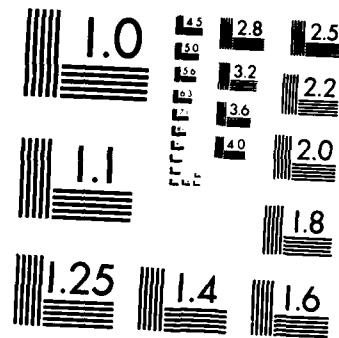
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Special Techniques for the Auger Analysis of Microelectronic Devices

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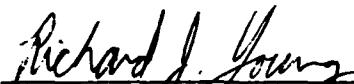
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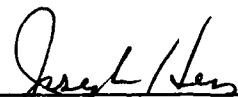
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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.



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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Microelectronic devices are becoming more complex and device features are getting smaller as the level of integration continues to increase. Although scanning Auger microscopy has been applied extensively to the analysis of microelectronic devices with a great deal of success, the analysis of current and future devices is presenting new challenges. The major limitations are: (1) features of interest in microelectronic circuits are often ~ | | |

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19. KEY WORDS *(Continued)*

20. ABSTRACT *(Continued)*

- comparable in size to the beam diameter of commercial Auger microprobes, and (2) the electron beam tends to drift about on the specimen surface because of mechanical instability and differential thermal expansion of the apparatus. In this technical report, we present information on two different techniques that were developed to overcome these limitations. In the specimen modulation technique, the modulating signal is applied to the electrically isolatable regions of a device instead of to the electron energy analyzer. This method of modulation permits the detection of only the Auger electrons that are emitted from the modulated region. Spurious contributions from adjacent areas inadvertently illuminated by the analyzing beam are suppressed. In the position modulation technique, the analyzing beam is scanned repetitively across the feature to be analyzed, and the Auger signal is synchronously detected at the scan frequency. The resulting Auger signal magnitude is shown to be unaffected by beam drift. This method of signal detection eliminates the error and uncertainty caused by beam instability during long-term depth profiling, but it is applicable only to specimens with certain geometries.

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PREFACE

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I. INTRODUCTION

The scanning Auger microprobe (SAM) provides spatially resolved elemental analyses of specimens. When combined with ion etching, elemental distribution in all three spatial dimensions can be determined. In the conventional method of Auger depth profiling, the analyzing beam is set at a point of interest and the peak-to-peak Auger signal amplitudes of elements are recorded as a function of time, whereas the surface is sputtered by an ion beam. A plot of Auger signal amplitudes versus sputtering time represents elemental concentrations as a function of depth. Unfortunately, the usefulness of commercial SAMs for the characterization of small features is limited both by the minimum usable diameter of the analyzing electron beam and by drift of the analyzing beam relative to the specimen as a result of mechanical and thermal instabilities in the instrument. In this report, two techniques devised to overcome the limitations imposed on SAMs by beam diameter and beam instability are described.

If the electron beam is of comparable or larger size than the feature of interest, then Auger signals from adjacent areas may contribute to observed Auger spectra. The specimen modulation technique is applicable to specimens, such as microelectronic devices, which have regions of interest that are electrically isolated (Ref. 1). The modulating signal usually applied to the Auger electron analyzer to facilitate electron detection is instead applied to a structure of interest, e.g., the gate of a microwave field effect transistor (FET). Only Auger signals from the region of interest are then detected by the phase-sensitive detector; interfering signals from adjacent regions are suppressed. Specimen modulation thus increases confidence in the origin of Auger spectra and helps overcome the limitation imposed by finite beam diameter.

Instability in the position of the analyzing beam is detrimental because minor movement can shift the beam away from the feature of interest. As a result, beam instability is an especially serious problem when a well-resolved compositional profile of a small feature is desired. The reason is that good

depth resolution requires low sputter rates, which translates into long sputtering time and consequently into more opportunity for the beam to move away from the region of interest. By use of the position modulation method, the sensitivity of Auger signal amplitudes to beam position drift for certain types of samples is eliminated, albeit at the expense of a reduction in signal-to-noise ratio. The position modulation technique involves sweeping the analyzing beam repetitively over a feature of interest. A second lock-in amplifier, with the sweep frequency as its phase reference, produces an output signal insensitive to beam position.

II. BACKGROUND DISCUSSION

A. SPECIMEN MODULATION

Auger electrons constitute only a small fraction of the total number of secondary electrons excited by the analyzing electron beam in an Auger spectrometer. Phase sensitive detection of the secondary electron current is usually employed to differentiate the spectrum and, thus, to reduce the slowly varying, and large, secondary electron background associated with Auger peaks. Phase-sensitive detection requires modulation of the detected signal, and the modulating voltage is usually applied to the electron energy analyzer. Modulation may, however, be applied equivalently to the specimen (Ref. 2).

B. POSITION MODULATION

The principle of position modulation is illustrated in Fig. 1, in which the feature of interest is a strip of element A deposited on a substrate of element B. In the position modulation technique, the analyzing electron beam is scanned repetitively across the feature of interest (Fig. 1a) to generate a secondary electron signal that is periodic. This periodic secondary electron signal contains components at the scan frequency corresponding to the Auger electrons emitted by elements present along the scan line (Figs. 1b and 1c). When detected with a lock-in amplifier (Fig. 1d), the amplitude and phase of the Auger signals of a particular feature depend on where it is found on the scan line. It should be noted that the periodic signals of A and B are out of phase and, therefore, their Auger signals have opposite signs. This phase information is critical for distinguishing between elements within and outside the feature of interest. More important, it can be shown that the magnitude of the signal produced by position modulation is independent of the position of the feature and, therefore, unaffected by beam drift as long as the feature stays within the scan line.

The effect of position modulation is to multiply the ordinary derivative Auger signal, $dN(E)/dE$, by a factor determined by specimen geometry. The peak-to-peak amplitudes of the in-phase and quadrature Auger signals as the

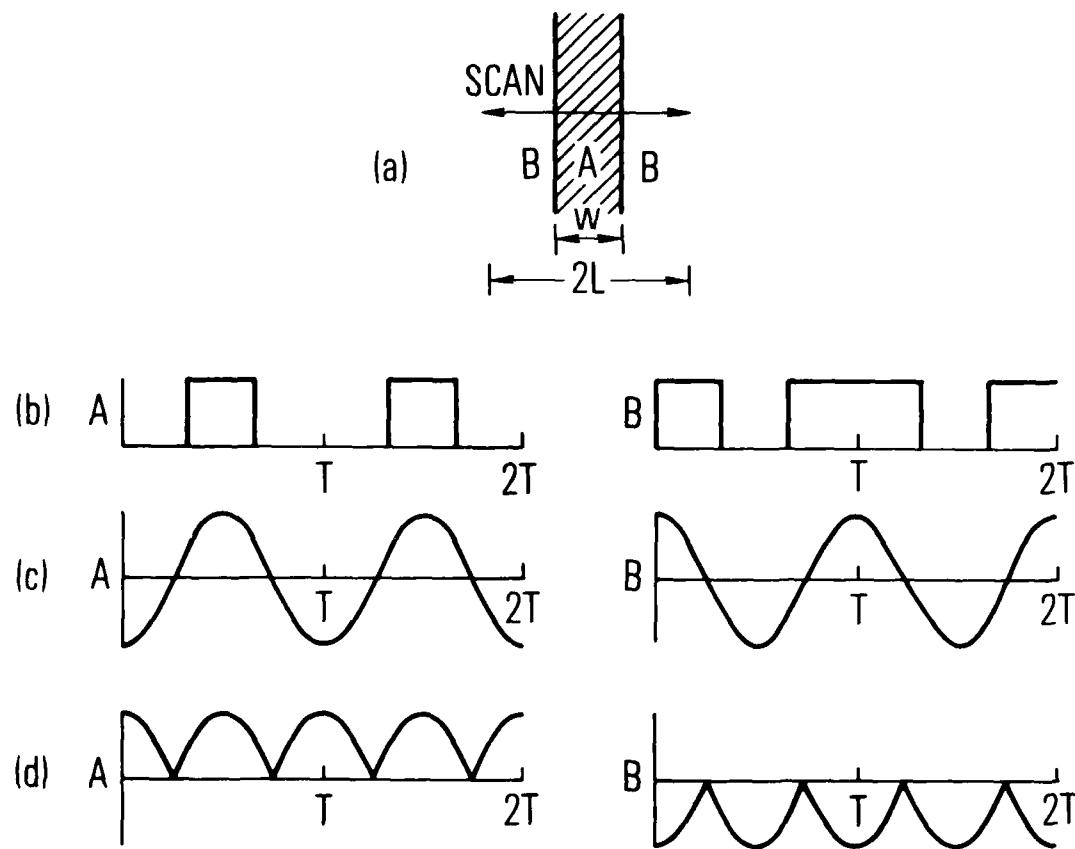


Fig. 1. Principles of Position Modulation

- The analyzing electron beam scans repetitively across a feature of width w composed of element "A" on a substrate of element "B". The beam scans along a line of total length $2L$ in a time T .
- As the spectrometer scans sequentially through electron energy regions corresponding to elements A and B, Auger signals periodic with the scan frequency are produced.
- These periodic signals have components at the scan frequency arising from elements A and B, but with different phases corresponding to their different positions along the scan line.
- The lock-in amplifier synchronously chops signal components at the scan frequency. With proper phase adjustment and filtering, dc levels corresponding to elements A and B are obtained as the spectrometer scans through the appropriate energy ranges. In the case illustrated, these signals have opposite phases.

electron analyzer scans through the energy ranges corresponding to elements of interest are denoted by S_I and S_Q . The sign of S_I or S_Q is defined as positive if the negative extremum of the derivative Auger signal occurs at higher kinetic energy than the positive extremum. The position-modulated output signal can be calculated explicitly for certain specimen geometries of interest. Consider, for example, a "linear" feature such as a gate metallization on a microwave FET. The feature has a width, w , and may have a layered structure, but is assumed to have uniform composition in planes parallel to the substrate. The electron beam is assumed for convenience to have a square cross-section of side D . (This assumption does not affect the argument and simplifies the mathematics.) The beam is scanned across the feature along a line of length $2L$. The following quantities are computed and stored:

$$\sqrt{(S_I^I)^2 + (S_Q^Q)^2} = (4\sqrt{2} L/\pi^3 D) \sin(\pi D/2L) (1 - \cos(\pi w/L))^{1/2} dN(E)/dE \quad (1a)$$

the signal magnitude, and

$$\begin{aligned} \theta &= \arctan(S_I^I/S_Q^Q) \\ &= \pi/L (1 + r + w/2) \end{aligned} \quad (1b)$$

where θ , the signal phase, lies between $-\pi/2$ and $+\pi/2$. The parameter "l" is the distance from the start of the beam line scan to the edge of the feature. Beam drift is manifested as a change in "l". The parameter "r" is the adjustable phase of the lock-in amplifier.

Some general features of the position modulation method are apparent from Eqs. (1a) and (1b). With position modulation, Auger signals of a given element in different portions of the scan can cancel. In fact, Auger signals vanish for elements present everywhere along the scan line. If an element is present only outside of the strip rather than in the strip, the corresponding Auger signal amplitude is unchanged, but the phase is reversed. Consequently, the sign (phase) of the Auger signal is an indication of whether an element is inside or outside of the region of interest.

The most striking aspect of position modulation is that the Auger signal amplitudes are independent of drift in electron beam position, unless the beam scan line drifts completely off the strip. In a typical application, when small features are to be analyzed, one often must have a beam diameter approximately equal to the feature width, i.e., $w = D$. Without position modulation, position drift of one beam diameter would then result in the complete loss of Auger signals from elements within the feature! With position modulation, Auger signal amplitudes will not change, according to Eq. (1a). By use of position modulation, beam drift will result in a change in signal phase. Phase information is stored along with signal amplitude, and can be employed to distinguish between elements within and outside of the feature of interest.

Depth profiles are obtained by combining position modulation with ion etching, similar to the conventional Auger depth profiling method. In the situation represented in Fig. 1, a conventional Auger depth profile taken through the strip will show a decrease in the concentration of element A, and the emergence of substrate element B, as the strip is sputtered away. In the position-modulated depth profile, both A and B will be detected initially, but their Auger signals will have opposite signs. As the strip is sputtered away, the amplitudes of the periodic signal components of both A and B vanish, and, thus, the position-modulated Auger signals of both elements A and B disappear together.

The position-modulation technique does have certain limitations. Decreased sensitivity to beam drift is obtained at the cost of degradation in signal-to-noise ratio. The decrease in signal amplitude relative to a conventional detection system (and, therefore, the degradation in signal to noise ratio, if the time constant of LI#1 is not changed) may be evaluated for any set of scan parameters from Eq. (1a). For example, if $w = D = 1/3(2L)$, then the signal-to-noise ratio decreases by a factor of 0.30. The application of position modulation is restricted to certain favorable specimen geometries, such as the long, narrow strip assumed in the derivation of Eq. (1). This particular geometry does, however, correspond to some specimens of practical interest.

III. EXPERIMENTAL CONSIDERATIONS

No significant modifications to the Auger system are necessary to implement either specimen-modulated or position-modulated data collection. A Z80-based microcomputer system developed in the Chemistry and Physics Laboratory of The Aerospace Corporation is used to control the electron energy analyzer, to collect Auger data for conventional depth profiles, and for specimen and position-modulated depth profiles. For the acquisition of position-modulated data, the computer acquires the peak-to-peak amplitudes of the Auger signal and its quadrature, stores the energies at which the signal maxima and minima occur, and monitors the sputtering time. Position-modulated depth profiles are computed and plotted from the stored data.

A. SPECIMEN MODULATION

Specimen modulation basically requires only that a vacuum feed-through electrical connection to the specimen be available. The specimen structure chosen for selective Auger analysis must, however, be capable of supporting an ac modulating potential, i.e., it must not present a low impedance path to ground. The modulating signal typically has a peak-to-peak amplitude between 2 and 10 volts and a frequency between 2 and 20 kHz. The insulated gate of a metal oxide semiconductor (MOS) FET is well suited for analysis. In order to apply the modulating signal to the drain or source of a FET, it is necessary to bias the gate to prevent conduction of the modulating signal to ground through the channel. Specimen modulation can be applied to the Schottky gate metallization of a metal-semiconductor (MES) FET even though the gate diode causes half wave rectification of the modulating voltage because the resulting wave form still has a component at the modulation frequency.

B. POSITION MODULATION

The experimental configuration of the Perkin-Elmer/Physical Electronics model 590 SAM for position modulation measurements is illustrated in Fig. 2. The SAM is used in the line-scan mode, and the electron beam scans repeatedly across a feature of interest. The electron energy analyzer sweeps through the

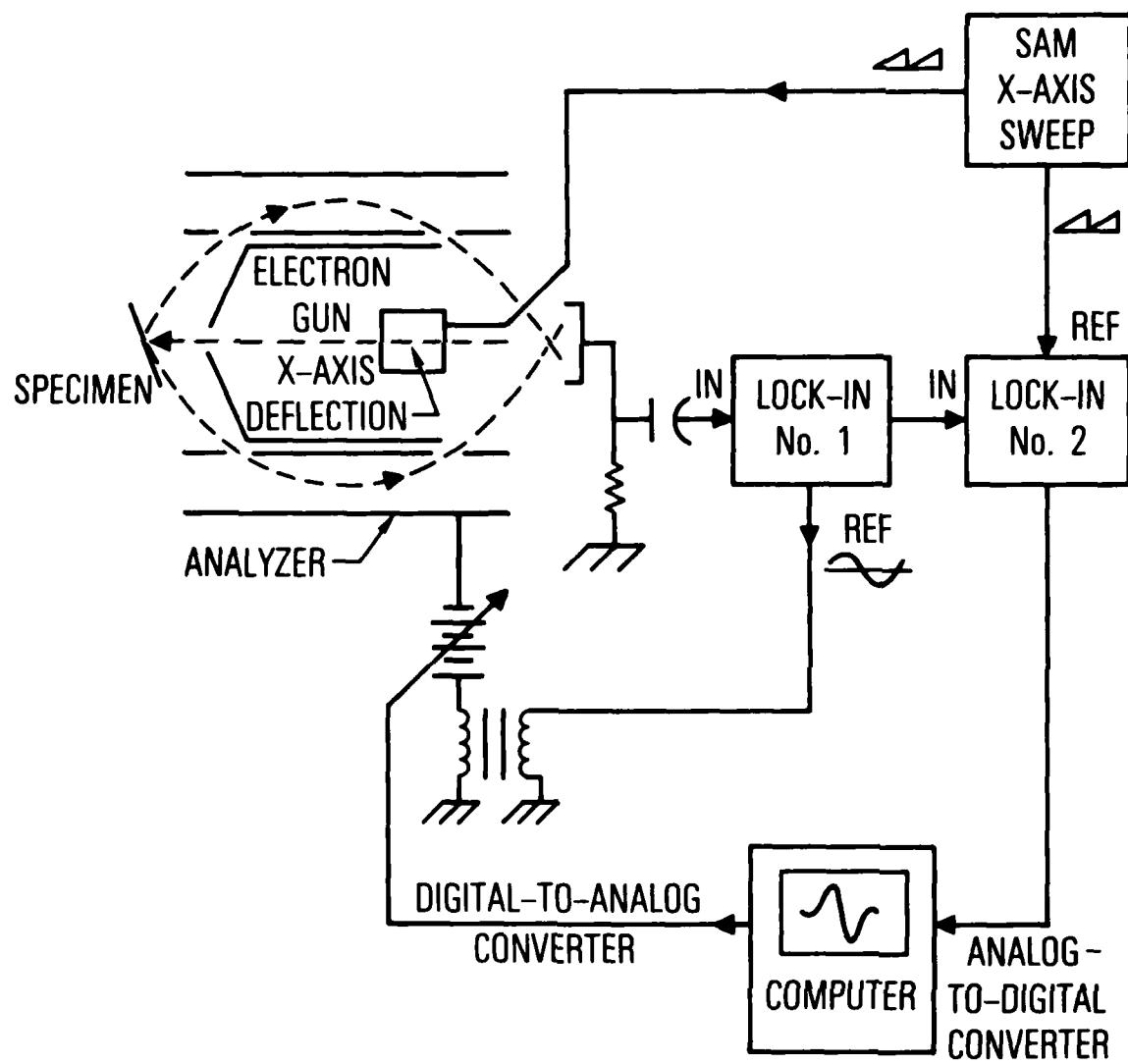


Fig. 2. Experimental Configuration of SAM for Position Modulation.

energy ranges corresponding to elements to be detected. The first lock-in amplifier (LI#1) is a component of the Auger system that is not fundamental to the position-modulation technique. It is used to differentiate the secondary electron spectrum with respect to energy. Differentiation reduces the large, slowly varying background that would otherwise interfere with signal amplification. In the position-modulation technique, the energy-derivative Auger signal is the input to the second lock-in amplifier (LI#2), which derives its phase reference signal from the beam line scan. Because we want to determine magnitudes and phases of Auger signals as defined in Eq. (1), LI#2 is a "quadrature" lock-in amplifier providing two synchronously detected outputs that differ as a consequence of a precise 90-deg, relative phase shift in the reference signal (Ref. 3).

The output of LI#1 is just a "normal" Auger signal, representing the concentration of an element averaged over the scan line, and it may also be stored by the system computer. For a particular element, the corresponding output of LI#1 vanishes only if the concentration of the element actually goes to zero at all points along the scan. Possible ambiguities in position-modulated depth profiles may be further reduced by considering these more conventional data along with position phase information.

IV. RESULTS AND DISCUSSION

A. SPECIMEN MODULATION

The ability of the specimen modulation technique to image electrically isolated regions of a specimen selectively is illustrated by the electron micrographs of a vertical metal oxide semiconductor (VMOS) FET. The general structure of the device is indicated in Fig. 3a. The SiO_2 "glassivation" that originally covered the chip was first removed using a standard HF/NH₄F etch. The secondary electron micrograph of Fig. 3b shows the general features of the FET structure. For reference, the gate lead exits toward the top at the right side of the micrograph. A conventional Auger elemental map of aluminum, obtained using analyzer modulation, is presented in Fig. 3c. Both gate and drain structures are clearly visible. The Auger aluminum micrograph of Fig. 3d was obtained using specimen modulation applied to the gate. Only the gate metallization is visible.

B. POSITION MODULATION

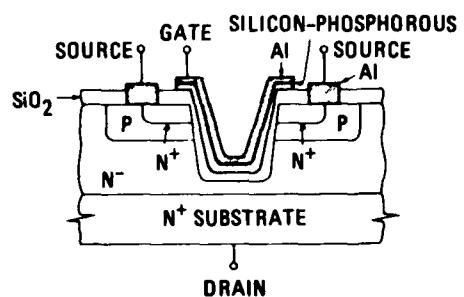
The basic concept of position modulation was verified experimentally by scanning the analyzing electron beam across a gold strip deposited on GaAs. The length of the scan was about three times the width of the strip. The MNN gold Auger peak at 69 eV was monitored, whereas the position of the strip relative to the scan line was changed by using the micrometer adjustments of the SAM specimen stage. The Auger signal magnitude and phase, as defined in Eq. (1), are shown as a function of strip position in Fig. 4. The signal magnitude is indeed independent of position, whereas the phase changes in agreement with Eq. (1b). The change in phase angle is, indeed, linear with change in strip position. The slope of the phase angle as a function of position measured from Fig. 4b is 6.5, in good agreement with the value 2π calculated from Eq. (6b). The apparent discontinuity in phase angle evident in Fig. 4b is simply a consequence of the definition of Eq. (1b).

A gold strip approximately 10 μm wide, deposited on GaAs, was profiled using position modulation. In the depth profile obtained from this specimen

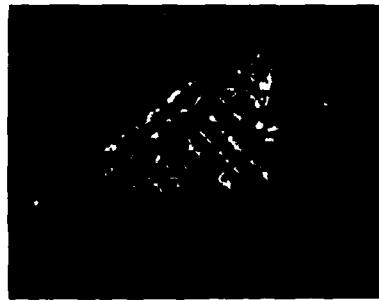
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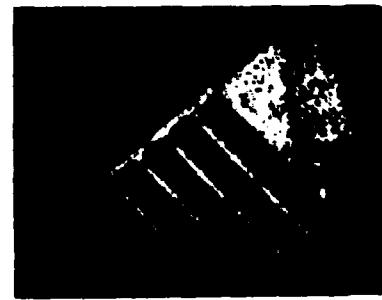


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ALUMINUM AUGER MAP
ANALYZER MODULATION

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ALUMINUM AUGER MAP
SAMPLE MODULATION-GATE

Fig. 3. Specimen Modulation Micrographs Obtained from VMOS Power FET.

- a. Structure of device.
- b. Secondary electron image.
- c. Aluminum LVV Auger map, analyzer modulation.
- d. Aluminum LVV Auger map, specimen modulation, applied to gate.

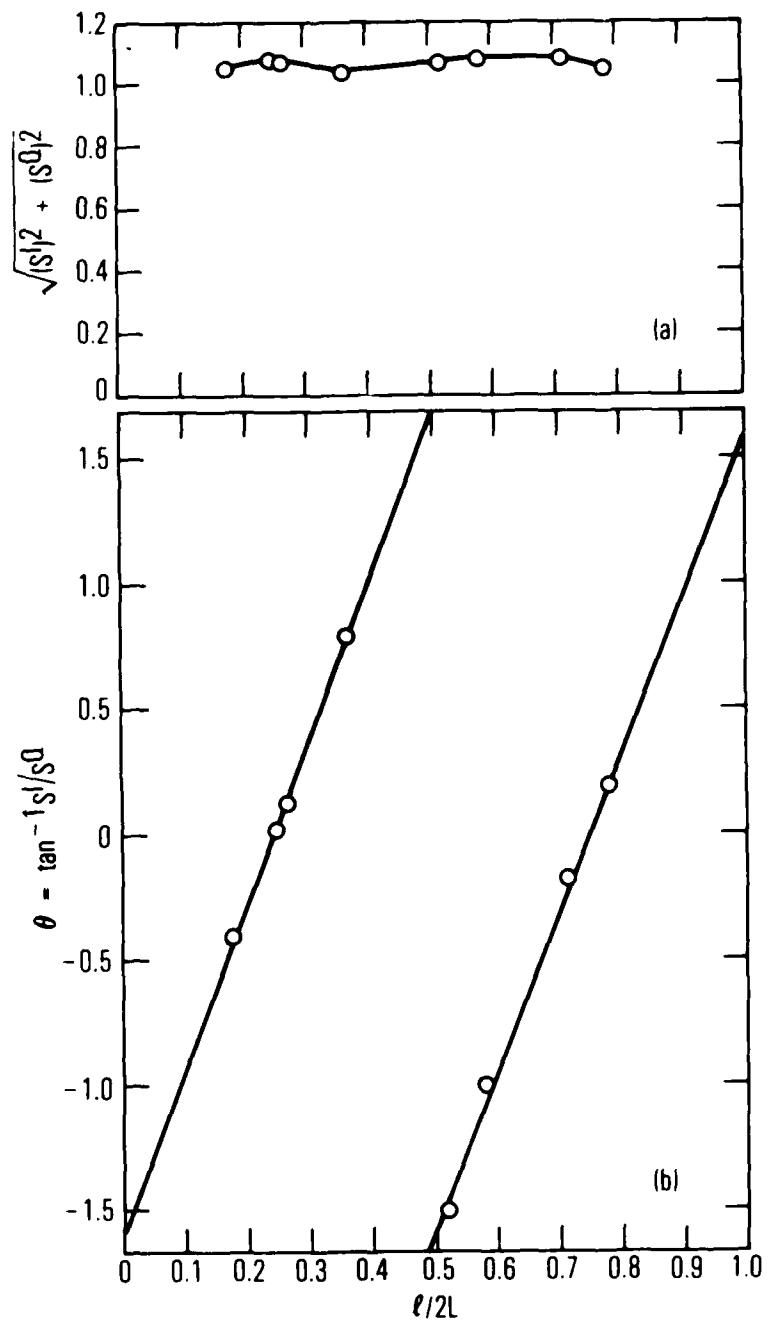


Fig. 4. Auger Signal Magnitude. (a) Auger signal phase and (b) function of position of a gold strip along scan line. Note that the signal magnitude is essentially independent of position.

(Fig. 5), Auger signals of one relative phase are represented by filled squares and those of the opposite phase by open circles. The phase of the Auger gold signal is opposite to the phase of the gallium, arsenic, and oxygen signals. The Auger signals all go to zero as the gold is sputtered away. Some ambiguity in data interpretation is inherent in the position modulation technique. For example, gallium and arsenic in the strip would not be clearly distinguishable from the signals from the substrate. We have used as an example a simple case in which a given element is present only in a particular region and has a uniform composition within that region.

It was found that the analyzing electron beam in the SAM can drift in any direction with respect to the specimen surface. The position-modulation technique is applicable if a specimen feature to be depth profiled has one dimension comparable to the beam diameter. The specimen is oriented so that the beam scans along this short dimension. In the perpendicular direction, the feature of interest is taken to be of uniform width and much longer than the distance characteristic of beam drift. These conditions, although apparently somewhat restrictive, are often satisfied in situations encountered in the analysis of microelectronic devices. Some prior knowledge of specimen composition in such devices is also often available.

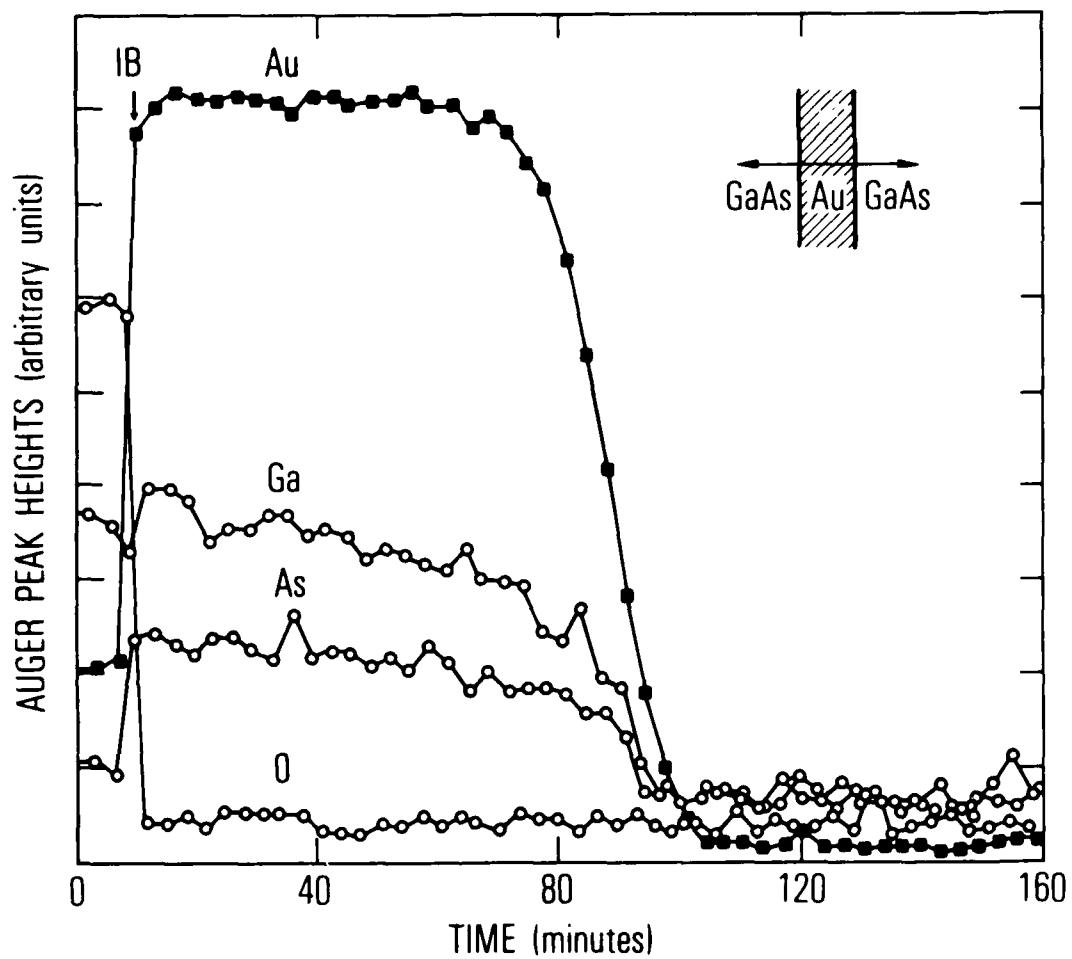


Fig. 5. Auger Sputter Depth Profile, Position Modulation, and Au Metallization on GaAs. Auger signals of one phase (Au) are plotted as solid squares, and signals of opposite phase (O, Ga, As) are plotted as open circles. Oxygen is present only at the surface and is sputtered away very quickly.

V. SUMMARY AND CONCLUSIONS

Both specimen and position modulation permit the experimenter to compensate for limitations of commercial Auger microprobes, especially in the analysis of microelectronic devices. With specimen modulation, confidence in the spatial origin of Auger signals is gained for those specimens in which regions of interest can be separately connected to a modulating signal. Position modulation is also applicable in experimental situations where regions of interest are not electrically isolatable. Specimens must, however, satisfy requirements of geometry imposed by the technique. Decreased signal-to-noise ratio, and additional complexity in data interpretation, are exchanged for immunity to beam drift.

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